GREENHOUSE GAS EMISSION ANALYSIS FOR HEATED PAVEMENT SYSTEM

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PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

ABSTRACT

Anthropogenic greenhouse gas (GHG) emissions have become significant environmental indicators in analyzing the comparative environmental impacts of conventional and newly developed alternative systems or techniques. Life Cycle Assessment (LCA) is considered an accepted and systematic methodology to calculate the amount of carbon released from all the processes of a system/technique, helping users select the best environmental-friendly alternative. The use of automated heating based snow removal systems is gaining attention as an alternative strategy to traditional ice and snow removal practices such as the use of anti-icing chemicals and snowplowing vehicles. Most previous studies on heated pavement systems have focused on their efficiency and economic evaluation, but few studies have investigated their environmental impacts in a systematic manner. Considering the energy consumptions associated with heated pavement systems, their environmental impacts should be assessed over the life cycle before they could be implemented in airport pavement applications. This study employs a partial LCA methodology to assess the GHG emissions from various operations of energy sources used in geothermal heated pavement systems and their environmental impacts in contrast with traditional snow removal operations, Detailed discussions are presented in the context of developing an environment assessment framework to help users select the most environmental-friendly snow removal system.

INTRODUCTION

Snow removal techniques can broadly be divided into de-icing and anti-icing techniques. De-icing of roadway, airport runway or other traffic surfaces typically involves the use of equipment and chemical reagents to remove snow, frost or ice in order to increase traffic safety [1]. It includes both mechanical and chemical application. Mechanical snow removal technique diverts snow from the traffic area to other locations by using snow blower and snow plow; chemical snow removal involves the application of ice melting reagent, such as using salt to get rid of snow and prevent snow reforming in a period of time [2]. Snow removal is really critical to airports, because the presence of snow, ice or slush on airfield surfaces (runways, taxiways, etc.) will cause serious situations resulting in potential airplane incidents [3]. Airports typically employ snow plows, snow blowers and chemical sprayers for snow/ice removal during traffic operations.

Apart from mechanical methods and chemical treatments, the use of a heated pavement system is being explored as an alternative way of removing snow and ice. Heated pavement systems include electrically heated pavements and hydronic pavement heating. Hydronic heated pavement system uses heated fluid flowing through the pipes to heat the land surface [4]. It can be classified based on different heating sources, the most common being the geothermal energy, which is the focus of this study as well. Geothermal heated pavement system applies ground source heat pump (GSHP) by circulating hot water warmed up by geothermal energy through pipes in the pavement in order to heat up the pavement and melt the ice. Geothermal energy is thermal energy generated or stored in the ground. Geothermal heating uses the geothermal energy directly as heating source for various applications [5]. GSHP can supply space heating by accessing heat in the soil. It is applied in regions that do not have access to high temperature geothermal resources. GSHP takes the heat absorbed in the land from solar energy through the use of a heat exchanger. Ground heat exchanger has two types of systems, direct exchange

geothermal system and closed loop geothermal system. In this study, closed loop system is not considered, considering its low efficiency, longer and larger pipe requirements, and high construction fee. Accordingly, this paper focuses on direct exchange system based geothermal heated pavement system. Direct exchange system is achieved through a single loop, circulating fluid, contacting with the ground directly. There are two kinds of piping systems, namely, horizontal and vertical systems. The depth of horizontal heat exchangers is 3 to 8-ft, while the vertical heat exchangers require a depth of 100 to 500-ft [6]. It has been claimed that the temperature in the ground below 20-ft is similar to the mean annual air temperature at the latitude at the surface [7]. The vertical direct exchange geothermal system is considered in this study.

Recent studies on airport heated pavement systems enlist their benefits as enhancing safety for aircraft, increasing airport capacity during winter operation, and decreasing snow removal time [8]. Although, most previous studies on heated pavement systems have focused on their snow removal rate and economic evaluation, only few studies investigated their environmental impacts in a systematic manner, and even fewer studies focused on their GHG emissions. Since significant amounts of energy are required to heat up the airport area during winter maintenance operations, a study on the GHG emissions released by heated airport pavement systems is vital. Considering the global significance of the climate change impacts and global warming issues, assessing the GHG emissions of heated pavement systems and traditional snow removal systems might give airport companies or heated pavement system operator better understanding of the global warming potential of both snow removal systems and help them choose the most environmental friendly snow removal systems.

OVERVIEW OF GREENHOUSE GAS EMISSIONS AND LIFE CYCLE ASSESSMENT

The global air temperature and ocean surface temperature has increased about 0.8 °C in the latest 100 years [9]. This continuous increase of global temperature is more commonly referred to as global warming. It was reported at the fourth International Panel on Climate Change (IPCC) that most global warming is caused by anthropogenic greenhouse gas (GHG), such as CO_2 emissions from power plant operations. Increasing human and industrial activities are reported to be the cause of increased GHG emissions leading to global warming and the associated serious environmental problems including sea level rising, expansion of subtropical deserts and species extinctions [10] [11]. In this study, CO_2, CH_4 and N_2O as critical GHGs, were assessed.

LCA provides a macroscopic view in studying the environmental impacts of products, techniques, processes and systems. Therefore it has been applied to analyze GHG emissions from different kinds of industries [12]. As a systematic and comprehensive model, the LCA has four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. This study analyzes the relative environmental impacts of traditional snow removal system and the geothermal heated pavement system by defining and establishing the system boundaries where the analysis is made: (1) fully understanding the amount of energy used and GHG emissions from the systems; (2) assessing the potential environmental effects in the inventory analysis; (3) evaluating the consequences of the inventory analysis and impact assessment of both systems to provide some of the suggestions and understandings to the system operators [13].

In order to calculate the quantities of energy and material input and the GHG output, there are three ways to approach the life cycle inventory, namely process-based LCA, economic input-out LCA, and hybrid LCA. The LCA approach adopted in this study is akin to a process-based LCA acknowledging its limitations: subjective boundary selection, lack of comprehensive data in many cases and its uncertainty. However, it does provide detailed information in the assessment of specific processes and it is good for product comparisons [14]. Since this article mainly focuses on comparing the GHG emissions of two different systems, the use of process-based LCA methodology is justified. Process LCA requires all inputs and outputs data for steps under the system boundary. However, the purpose of this study is not to conduct a full life cycle study, but to understand the differences in GHG emissions between two snow removal systems. Therefore, a partial process-based LCA will be employed in this study.

METHODOLOGY AND DATA SOURCE

This study only considers the operation phases of both traditional and heated pavement snow removal systems, which means that construction, maintenance, and rehabilitation phases are not included in the system boundaries. By limiting the system boundaries for both systems, only the systematic processes which contribute to GHG emissions are assessed. As both snow removal systems indicate, they have similarities in the processes of consuming energy to get rid of the snow/ice on the ground. Thus, for the sake of simplicity, both system life cycles are divided into two phases, energy supply life cycle and energy consumption life cycle. The energy supply life cycle is the life cycle of power plants, which support the energy for both snow removal systems and generate GHG. The energy consumption life cycle is the life cycle of both snow removal systems themselves, which consume the energy and release GHG, as shown in Figure 1.
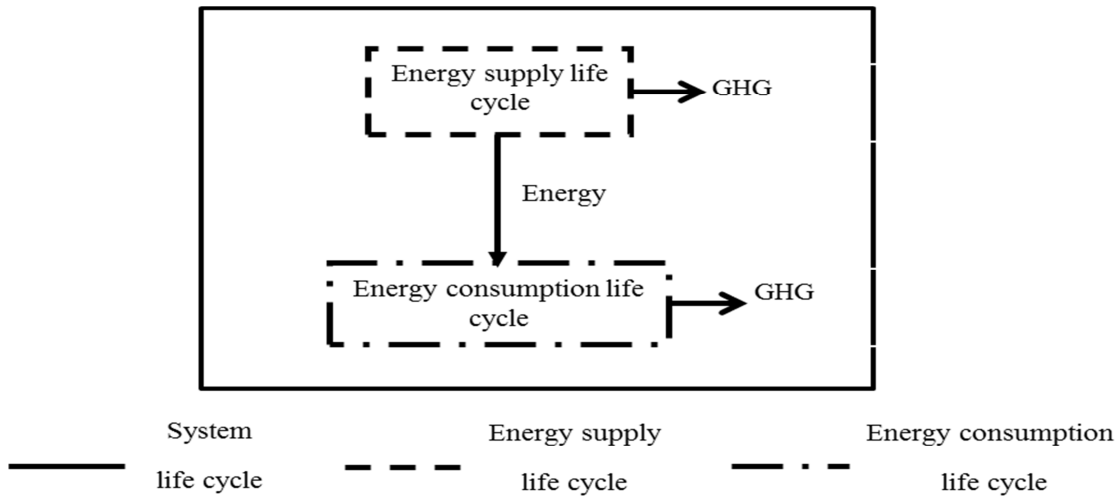

Figure 1. Life Cycle Boundaries

Before assessing the life cycle of both systems, system boundaries are established as follows [15]:

- Boundaries between the technological system and nature

- Geographical area

- Time horizon

Boundaries between the Technological System and Nature

Theoretically speaking, a complete life cycle starts with raw material extraction and but not part of the system. However, depending on the goal of the study, LCA can be excluded certain stages of life cycle and study specific stages in detail more closely related to the study objective. Thus, by allowing the goal of the LCA to determine the time horizon, most meaningful results can be obtained [16]. For example, in using LCA to analyze the carbon emissions from food production industry, the food planting life cycle might be excluded from the whole life cycle. Because the goal of study is to understand the carbon emission from the food processing life cycle, the raw materials extraction might not affect the results.

The end of the life cycle is when GHG released from the systems into the environment. Wastewater treatment plant and incineration plants are considered as parts of the technological system, which is seen as a stage in a life cycle, therefore, their GHG emissions need to be seen as the result of inventory. But there is no definition to include landfills as part of technological system, because emissions from landfills are considered neither inventories nor impact assessments [17]. In this study, landfill treatment of waste is excluded.

Geographical Area

LCAs have to be geographically restricted, since geography is a significant factor in LCAs in the following aspects:

- Various life cycle stages of a product may be manufactured in different places;

- GHG emissions from electricity production, waste treatment or transportation can be different from different locations;

- The sensitivity of the environment to pollution varies from place to place.

In this study, carbon emissions factors from different facilities and equipment of both heated pavement systems and traditional snow removal systems are based on facilities and organizations within the U.S. Also, GHG emissions from electricity production can vary from state to state within the US based on data from the U.S. Energy Information Administration (EIA).

Time Horizon

A time horizon, also known as a planning horizon, is a range of time from the start of assessment to the end [16]. The life time of the system or the product should be considered since it is connected to the system boundary and restricted to the life cycle. In this study, time horizon of life cycles considered will be the time both airport snow removal systems spend to melt snow under same study conditions and the time for deicing wastewater treatment.

LCA FOR TRADITIONAL SNOW REMOVAL MODEL

Traditional Snow Removal Model

Commercial service airport is the objective in this study. According to FAA records, when annual airplane operations exceed 40,000, snow clearing time for each runway in a commercial service airport is about 0.5 hr [3]. Snow plow, snow blower and chemical deicer truck are assumed to be used in removing snow for runway. Snow removal equipment is assumed to operate at velocity of 32 km/hr. The snow removal strategy considered in this study is to deploy snow plow to plow snow to side, followed by snow blower to get the snow off the runway, and to spray chemical deicer in the end. Because the snow removal time is 0.5 hr, it is assumed that 6 snow plows, each with an engine power rating of 708 kW, can go twice along one runway length to push the snow to the side with an operation time of 0.23 hr. Similarly, 2 snow blowers with a 820.3 kW engine power rating and 2 deicer sprayers with a 600 kW engine power rating traverse once to get rid of snow on the runway with an operation time of 0.11 hr.

Traditional Snow Removal System Boundary

As discussed previously, traditional snow removal operations involve the use of mechanical equipment, such as snow plow, snow blower to remove snow from airport traffic surfaces. Diesel oil is used for snow removal equipment operation, which is the energy input in the traditional removal system boundary. The system boundary of traditional snow removal system operation life cycle considered in this study is shown in Figure 2.
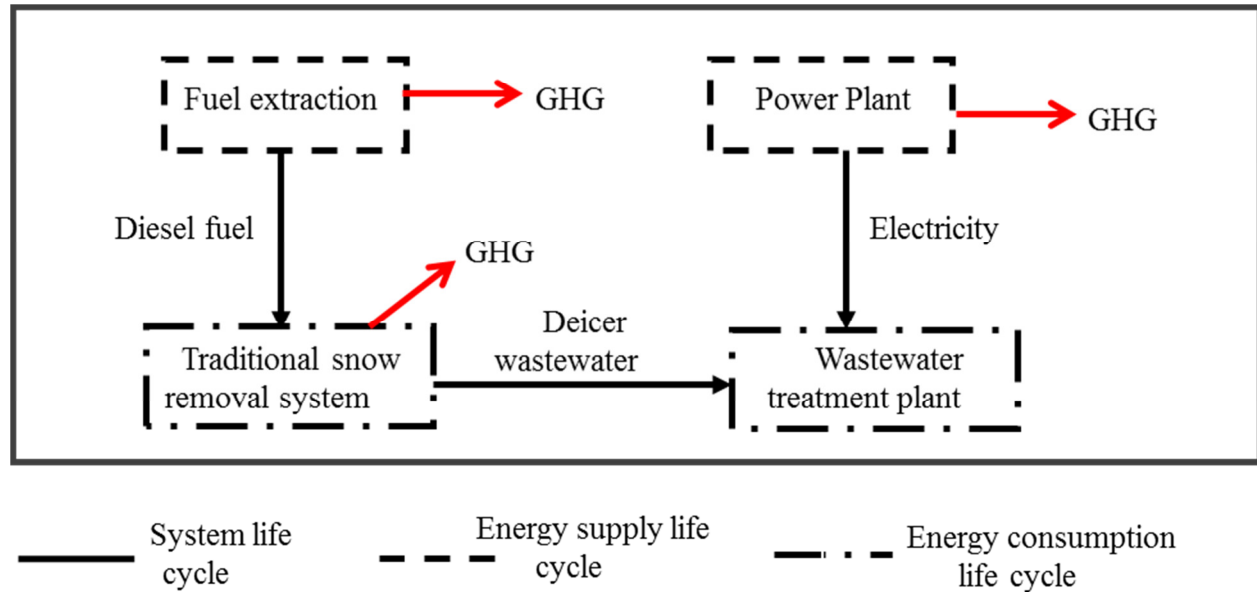

Figure 2. System Boundary of Traditional Snow Removal System Operation Life Cycle

- **GHG emissions from traditional snow removal system operations**

To understand the amount of GHG released from traditional snow removal system, the amount of diesel oil consumption needs to be estimated. The amount of fuel consumption can be estimated as [18]:

$$FC = RP \times 0.3 \times LF$$

where:
FC is Fuel Consumption (per hr);
RP is equipment rated power (kW);
0.3 is unit conversion factor (per kWh);
LF is an engine load factor (push loading scrapers, and most land clearing applications are rated 'medium scale' for which load factor is 60%).

The conversion factors of CO_2 emission for the diesel fuel can be calculated as [18]:

$$GHG\ emission = FC \times 0.00268$$

where the conversion factor for diesel fuel is taken as 0.00268

Therefore, to remove about 1.7 million ft^2 areas with 1 inch deep snow in 0.5 hr, the use 6 snow plows, 2 snow blowers and 2 deicer sprayers are required. The GHG emissions resulting from snow removal operations are shown in Table 1 below, the total GHG as CO_2 emissions being 0.62 t:

Table 1. GHG Emissions from Traditional Snow Removal System Operations

Equipment	Snow Plow	Snow Blower	Deicer Sprayer
Energy demand /kW	708	820.39	600
Fuel consumption/ L	172.04	34.72	24.3

- **GHG emissions from fuel extraction phase**

The emission factor of fuel extraction can be calculated as (0.778 $kgCO_2eq$/kWh -0.756 $kgCO_2eq$/kWh [26] [27]) = 0.022 $kgCO_2eq$/kWh, and petroleum is 3.35 kWh/L, so GHG emission is 0.0737 kg/L. Since fuel consumption is 231.06 L, the total GHG emission from the fuel extraction phase of the traditional snow removal system life cycle is 17.03 kg, which is 0.017 t CO_2eq.

- **GHG emission of wastewater treatment**

Since at temperature of 10°F, deicing demand is 3 gal/1000 ft^2 runway of ethylene glycol (EG) [19], and 60% of deicing wastewater is assumed to be captured [20], the total EG demand is 5,231gal. The case of 50% EG deicing fluid is considered as an example, and the weight of the EG component is 4.7 lb/gal [21]. The COD content of ethylene glycol deicer can be calculated as:

COD (lbs) = Chemical (lbs)×Chemical Molecular Weight (mole/g)×ThOD×O_2 Molecular Weight (g/mole)

where:

ThOD of EG is 2.5;

EG molecular weight is 0.016 mole/g;

O_2 molecular weight is 32 g/mole.

The total wastewater COD is 2,874 kg. Aerobic biological treatment is assumed in this study, and 0.8 kWh electricity demand per kg COD is assumed for aerobic treatment. Therefore, the total electricity demand for deicer wastewater treatment will be about 6,898 kWh. By using the GHG emission factors of power plant, the GHG emissions from wastewater treatment are shown in Table 2:

Table 2. GHG Emissions from Airport Pavement Deicer Wastewater Treatment

Electricity form	Coal	Natural Gas	Diesel Oil
GHG emission /t	6.83	2.90	5.37

GHG emissions of traditional snow removal system applied in airport runway snow removal life cycle

By combining all the stages of traditional snow removal life cycle discussed above, as the total GHG emissions from the traditional snow removal life cycle is obtained and summarized in Table 3.

Table 3. GHG Emissions (t) of Traditional Snow Removal System Applied in Airport Runway Snow Removal Life Cycle

Life cycle stages	GHG Emission /t		
Snow removal	0.62		
Fuel extraction	0.017		
Wastewater treatment	6.83[1]	2.90[2]	5.37[3]
Total	7.47	3.53	6.01

Note: [1]electricity generated by coal power plant; [2]electricity generated by natural gas power plant; [3]electricity generated by diesel oil power plant.

LCA FOR GEOTHERMAL HEATED PAVEMENT

Geothermal heated pavement model

The case of Vienna Schwechert International Airport Runway is used as an example for estimating the GHG emissions from geothermal heated pavement model. Although the airport is not located in US, this study only uses one of its runway areas as an example, which does not have GHG emissions contribution. To remove 1 inch deep snow (at an ambient temperature of 6 °F) covering Vienna Schwechert International Airport Runway RWY 16/34, with a length of 11,811-ft (3600 m) and width of 147-ft (45 m), is the goal of both snow removal systems. It is assumed that 1 unit of geothermal piping can heat 1320 in^2 area, as shown in Figure 3.
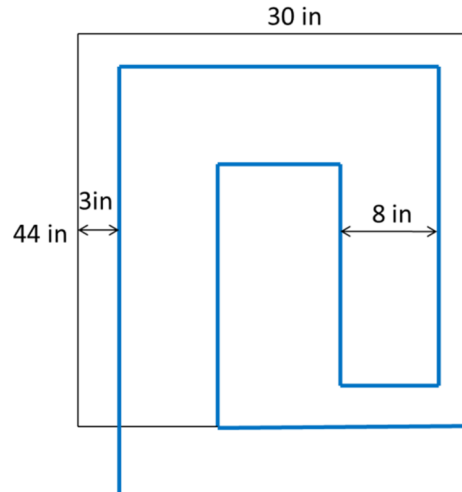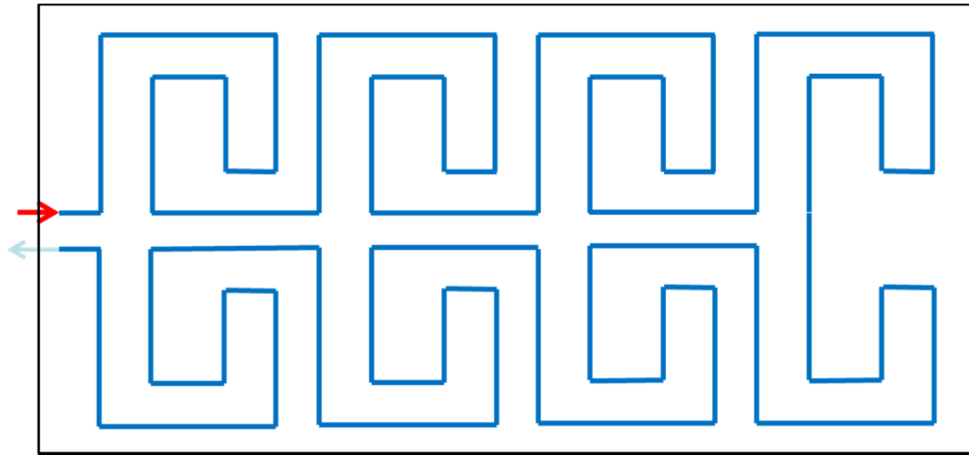
Figure 3. 1 Unit of Geothermal Piping

Figure 4. 1 Circuit of Geothermal Heating Area

A ¾ inch PEX pipe is assumed for hydronic heating in this study. For implementing a single circuit, this translates into a length of 300-ft maximum. There can be 18 units per circuit, whose length is 299-ft (<300-ft), and it can warm up 16-ft^2 of the slab area. This is depicted in Figure 4. To minimize the quantity of heat wells, 40 circuits are assumed to be set in 1 well. Water flow rate is assumed to be 1 gpm per circuit, and the total flow rate is 40 gpm per well, therefore, 1 well can warm up about 6,624-ft^2 of slab, as shown in Figure 5 below.
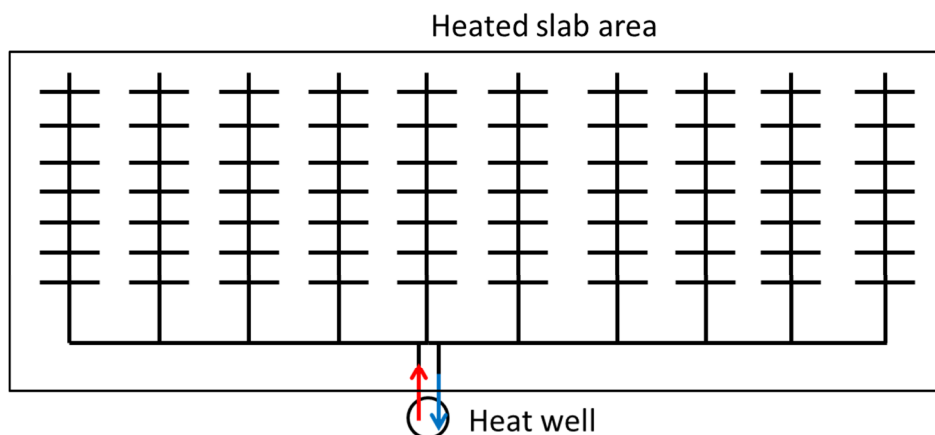
Heated slab area

Figure 5. Geothermal Heating Area per Heat Well

Since a single well can heat 6,624-ft^2 (615.4 m^2) area, 263 heat wells are required for warming up 162,000-m^2 runway area.

Geothermal Heated Pavement Systems Boundary

Vertical direct exchange geothermal system is operated by circulating water heated by the energy from the ground which does not need an extra heater. Thus, the only energy input is assumed to be pumping operation. In this study, electric pump is selected as the power supply device for circulating water in the geothermal heated pavement system. The system boundary of geothermal heated pavement system operation life cycle is shown in Figure 6.
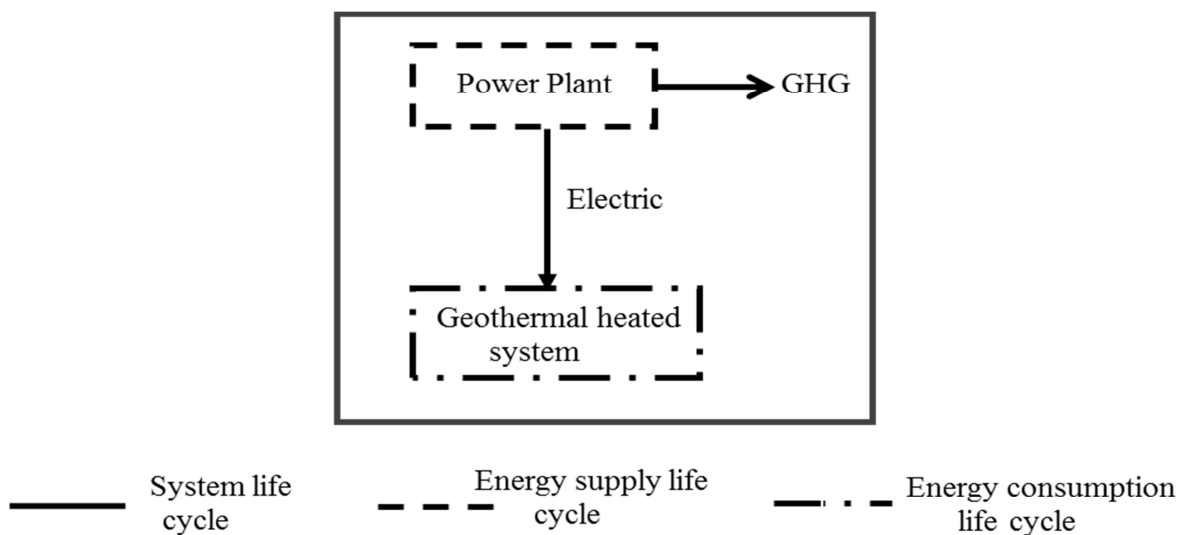

Figure 6. System Boundary of Geothermal Heated Pavement System Operation Life Cycle

As shown in figure 6, since direct exchange geothermal heated systems consume electricity for circulating water, there is no GHG released from the heated system directly. GHG emissions

in the system life cycle are from the energy supply life cycle, instead of energy consumption life cycle. Thus, it is significant to assess the life cycle of electric power plant in order to assess the GHG emissions from geothermal heated pavement system.

Because most power plants in the world burn fossil fuels such as coal, oil and natural gas to generate electricity, all three traditional fossil fuel electric power plants are analyzed in this study. In this partial life cycle study, three traditional fossil fuels based electric power plants life cycle can be simply defined into four stages: fossil fuel extraction, fossil fuel pretreatment, fossil fuel transportation and electricity generation.

Coal power plant carbon emission life cycle assessment

Because GHG emissions of power plant can be varied by different location, a power plant located in State of Iowa is analyzed in this study, and the life cycle of coal power plant analysis is based on previous study on life cycle assessment of coal-fired power production [22]. The stages studied include coal mining, coal preparation/cleaning, all necessary transportation of coal to power plant, and grid electricity production.

- **GHG emission factor of grid electricity production**

GHG emissions from electricity production is based on the data from US Energy Information Administration EIA-1605, grid electricity production of State of Iowa GHG emissions is 0.88 $kgCO_2eq/kWh$.

- **GHG emission factor of coal mining**

The Illinois No. 6 coal was chosen because it is representative of widely available bituminous coal in the U.S. About 62% of the coal in the U.S. is mined by surface mining, while 38% is obtained by underground mining [22]. A previous study showed that the LCA results between surface mining and underground mining was just slightly different [22]. Therefore this study only considers the surface mining as the coal fired power plant mining process. Since Pamela L.S [22] claimed that electricity demand is 0.0143 kWh/kg of coal mined, and diesel oil demand is 269 m^3/MMT of coal mined. Based on United Nation Framework Convention on Climate Change Clean Development Mechanism Project Design Document Form (CDM-SSC-PDD), diesel oil used for transportation GHG emissions was 2.7 $kgCO_2eq/L$, and 0.54 kg coal/kWh electricity produced was shown by US EIA [23]. Therefore, the GHG emissions from coal mining are calculated to be 7.02×10^{-3} $kgCO_2eq/kWh$.

- **GHG emission factor of coal washing**

Jig washing is the technique used in this LCA [22], GHG emission factor of coal washing is 1.03×10^{-4} $kgCO_2eq/kWh$.

- **GHG emission factor of coal transportation**

Transportation of coal by barge, train, or truck between the boundaries of the coal mining and power generation subsystems require energy and such transportation also generates emissions Data indicate that except for mining operation, coal transport by trucks is rare, which

is ignored in this analysis. The distance of coal transportation from mining to power plant is 48 km by railcar, and 434 km by ship. The GHG emissions factors of shipping transportation and railway transportation are 0.43 $kgCO_2eq/t\cdot km$ and 0.01 $kgCO_2eq/t\cdot km$, respectively [24]. Therefore, the GHG emissions of shipping are 0.1 $kgCO_2eq/kWh$ and railway is 2.59×10^{-4} $kgCO_2eq/kWh$.

The coal-fired power plant GHG emissions factors of each life cycle stages are listed in Table 4.

Table 4. GHG Emissions Factors of Coal Power Plant Life Cycle Stages

Life Cycle Stages	Carbon emissions factors	Percentage %	Unit
Surface mining	7.02×10^{-3}	0.70	$kgCO_2eq/kWh$
Coal washing	1.03×10^{-4}	0.01	$kgCO_2eq/kWh$
Shipping transportation	0.10	10.10	$kgCO_2eq/kWh$
Railway transportation	2.59×10^{-4}	0.03	$kgCO_2eq/kWh$
Electricity production	0.88	89.20	$kgCO_2eq/kWh$
Whole life cycle	**0.99**	**100**	**$kgCO_2eq/kWh$**

Natural gas power plant carbon emissions life cycle assessment

The life cycle of natural gas in this paper is based on the report, *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant Appendix: Process Modeling Data Assumptions and GaBi Modeling Inputs* [25]. Natural gas power plant life cycle is combined by natural gas extraction, natural gas pretreatment, liquefied natural gas (LNG) transportation and grid electricity production. Auxiliary boiler natural gas consumption is calculated to be 0.16 kg/MWh. A natural gas density of 0.042 lb/ft^3 [25] is used in this study.

- **Emission factor of natural gas extraction**

Sub stages of natural gas extraction are divided into the natural gas extraction and pretreatment phase: compression, dehydration, sweetening, flaring, natural-gas-drilling and pipeline operation. But oil/gas separation phase is not included, since data from the study [25] is missing and the carbon emissions portion of natural gas extraction is not critical. Energy requirement for natural gas dehydration is assumed to be electricity generated by the natural-gas-boiler. Since the objective in this study is GHG, H2S is not included. NG drilling operation is divided into Coal Bed Methane, Barnett Shale, Offshore, Associated Gas, and Onshore. In this study, a 2-phase 95%-efficiency compressor, whose power requirement is 187 horsepower per MMCF of natural gas, is chosen. By calculating all the emission data from different sub stages of extraction, the CO_2 emission factor of natural gas extraction is 6.18×10^{-4} $kgCO_2eq/kWh$, CH_4 and N_2O emission factors will be 3.65×10^{-3} $kgCO_2eq/kWh$ and 1.74×10^{-6} $kgCO_2eq/kWh$, respectively. Thus the total emission factor will be 4.27×10^{-3} $kgCO_2eq/kWh$.

- **Emission factor of natural gas pretreatment**

Natural gas pretreatment stage includes natural gas liquefaction and liquefied natural gas regasification. It was assumed that the LNG tanker is a 138,000-m^3 carrier and that propulsion is fueled by cargo boil-off and then supplemented with diesel fuel in Wartsila dual-fuel engines.

Carbon dioxide and NOX emissions are calculated from engine manufacturer specifications, assuming that the engines are running at 75% load (higher emissions than for 100 percent load). Total GHG emission factor is calculated to be 8.54×10^{-5} kgCO$_2$eq/kWh [25].

- **Emission factor of liquefied natural gas transportation**

LNG tanker berthing and LNG transportation are included in the natural gas transportation stage. The total GHG emission factor is calculated to be 1.35×10^{-5} kgCO$_2$eq/kWh.

- **Emission factor of grid electricity production**

Natural gas was assumed as the fuel used (versus fuel oil), and consumption of the auxiliary boiler is estimated to be 53,000 standard ft^3/hr based upon highest fuel consumption claims for two similarly sized boilers in the sited [25]. 23.8-ft^3/lb as the specific volume of natural gas, auxiliary boiler natural gas consumption is calculated to be 0.16 kg/MWh, and GHG emission factor is 0.42 kgCO$_2$eq/kWh.

The natural gas power plant GHG emissions factors of each life cycle stages are listed below in Table 5:

Table 5. GHG Emissions Factors of Natural Gas Power Plant Life Cycle Stages

Life Cycle Stages	Carbon Emissions Factors	Percent %	Unit
Natural gas extraction	4.27×10^{-3}	1.01	kgCO$_2$eq/kWh
Natural gas pretreatment	8.54×10^{-5}	0.02	kgCO$_2$eq/kWh
LNG transportation	1.35×10^{-5}	0.0032	kgCO$_2$eq/kWh
Grid electricity production	0.42	98.97	kgCO$_2$eq/kWh
Whole life cycle	**0.42**	**100**	**kgCO$_2$eq/kWh**

Fuel power plant carbon emissions life cycle assessment
Since oil fired power plant carbon emission factor highly depends on a particular (site-specific) power plant, this study assumed 0.778 kgCO$_2$eq/kWh as the GHG emission factor of fuel power plant based on previous study [26]. To confirm the applicability and use of this factor, it was compared with the EIA database. It stated that distillate oil (No.2) GHG emission factor of grid electricity production is 0.756 kgCO$_2$eq/kWh [27], which was 97.2% of the total GHG emission factor as shown in previous study. Therefore, it is reasonable to use 0.778 kgCO$_2$eq/kWh as fuel power plant GHG emission factor.

GHG emissions of geothermal heated pavement system applied in airport runway snow removal life cycle
To understand how much energy is needed to melt 1 inch of snow in hours, equation derived [28] for the required pavement heat output (qo) in Btu/hr·ft^2 is applied:

$$qo = qs + qm + Ar(qe + qh)$$

where:

q_s = sensible heat transferred to the snow (Btu/hr·ft^2);
q_m = heat of fusion (Btu/hr·ft^2);
A_r = ratio of snow-free area to total area (dimensionless);
q_e = heat of evaporation (Btu/hr·ft^2);
q_h = heat transfer by convection and (Btu/hr·ft^2).

The energy demand for snow removal is shown in Table 6:

Table 6. Energy Demand for Geothermal Heated Pavement System to Melt Snow

q_o (Btu/hr·ft^2)	q_s (Btu/hr·ft^2)	q_m (Btu/hr·ft^2)	A_r	q_e (Btu/hr·ft^2)	q_h (Btu/hr·ft^2)
204.7	9.8	74.6	0.7	0.25	171.6

Since the energy might have a 20% back and edge losses, so the actual energy demand to melt 1 inch snow in 1 hr is 246 Btu. Because the total area for 1 runway is 1.7 million ft^2 (162,000 m^2), the total energy demand to melt 1 inch snow is 428 million Btu. By using the geothermal heated pavement model discussed above, there are 263 heat wells demand and each heat well is 500-ft deep. The energy supplied by the geothermal vertical loop is calculated using [29]:

$$E = 0.00095 \times P \times m \times cp \times (\Delta T)$$

where:

E = energy supply (Btu/hr);
m = mass flow rate of water (9,200 kg/hr);
cp = specific heat of water (4.18 J/g·°C);
ΔT = outlet water temperature - inlet water temperature (10°C assumed);
P = energy loss from PEX pipes, soil and concrete slab (80% assumed).

Therefore, energy supply of 263 heat well is about 7.7×10^7 Btu/hr. And because to melt 1 inch and 1.7 million ft^2 of snow requires about 4.3×10^8 Btu, it needs 5.58 hr of operation. To pump 40 gpm of water to go through a 500-ft deep heat well, the horse power needed for the pump is calculated as:

$$Hp = Q \times H / 3960$$

where:

Hp = horse power of each pump;
Q = flow rate (40 gal/hr);
H = depth of heat well (500-ft)

The horsepower demand of each pump is 5.05 Hp, which is 3768 watts. Because 263 heat wells require 263 pumps, 5522 kWh is required to melt 1.7 million ft^2 of 1 inch depth snow in 5.56 hr. The GHG emissions resulting from using electricity produced by three traditional fossil fuels are shown in Table 7 below.

Table 7. GHG emissions of Geothermal Heated System Using Electricity for Operation

Electricity form	Coal	Natural Gas	Diesel Oil
GHG emissions (ton)	5.46	2.32	4.30

COMPARISON RESULTS

To compare both systems in removing same amount of snow, the comparative GHG emissions are summarized in Table 8:

Table 8. Comparison of GHG Emissions from Geothermal Heated Pavement System and Traditional Snow Removal System Comparison

	Electricity-Coal	Electricity-Natural Gas	Electricity-Fuel Oil
Geothermal Heated Pavement System GHG Emissions /t	5.47	2.32	4.30
Traditional Snow Removal System GHG Emissions /t	7.47	3.53	6.01

Thus, based on this preliminary study with acknowledged limitations, it is seen that the geothermal heated pavement system is more environmental friendly compared to the traditional snow removal system in removing 1 inch of snow covering 162,000 m^2 area of the runway.

SUMMARY: FINDINGS, DISCUSSIONS AND RECOMENDATAIONS

This study was carried out to study the GHG emissions of geothermal heated pavement system and traditional snow removal system. LCA is a technique to assess environment impacts of a system from cradle to grave. However, according to the purpose of understanding the differences between the GHG emissions of geothermal heated pavement systems and traditional snow removal systems only, a partial process-based LCA approach was adopted in this study, instead of a complete LCA. Specific assumptions were made, and preliminary findings tend to indicate that geothermal heated pavement may be more environmentally friendly compared to traditional snow removal system within the limited scope of this study.

FINDINGS AND DISCUSSIONS

- A side finding, which is not the focus of the study, is that natural gas power plants release lesser GHG emissions compared to coal and fuel power plants.

- Most of the GHG emissions in the traditional snow removal system are from deicer wastewater treatment plant which uses aerobic biological method.

- Based on the assumptions and specific conditions considered in this study, a geothermal heated pavement system using electric pump to run the system has lower GHG emissions than a traditional snow removal system in removing 1 inch of snow from airport runway surface at an ambient temperature of -6 °F.

RECOMMENDATIONS

- Future studies may focus on different weather conditions, snow removal equipment and strategies, and other potential factors that might influence GHG emissions of both systems.

- Some studies have concluded that the use of deicer chemicals on airport pavement surfaces tend to cause and/or accelerate distresses leading to more frequent repairs. This may increase the energy spent during the pavement maintenance phase. Therefore, it will be interesting to study the life cycle of both snow removal systems from this perspective.

ACKNOWLEDGEMENTS / DISCLAIMER

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